Two Energy Release Processes for CMEs: MHD Catastrophe and Magnetic Reconnection

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ABSTRACT

It remains an open question how magnetic energy is rapidly released in the solar corona so as to create solar explosions such as solar flares and coronal mass ejections (CMEs). Recent studies have confirmed that a system consisting of a flux rope embedded in a background field exhibits a catastrophic behavior, and the energy threshold at the catastrophic point may exceed the associated open field energy. The accumulated free energy in the corona is abruptly released when the catastrophe takes place, and it probably serves as the main means of energy release for CMEs at least in the initial phase. Such a release proceeds via an ideal MHD process in contrast with nonideal ones such as magnetic reconnection. The catastrophe results in a sudden formation of electric current sheets, which naturally provide proper sites for fast magnetic reconnection. The reconnection may be identified with a solar flare associated with the CME on one hand, and produces a further acceleration of the CME on the other. On this basis, several preliminary suggestions are made for future observational investigations, especially with the proposed KuaFu satellites, on the roles of the MHD catastrophe and magnetic reconnection in the magnetic energy release associated with CMEs and flares.

Subject headings: solar magnetic field, coronal mass ejections, MHD catastrophe

1. Introduction

Observations suggest that magnetic energy serves as a main energy source for solar active phenomena such as CMEs (see reviews by Forbes (2000) and Low (2001)), but it remains an open question how the magnetic energy is released. The accumulated magnetic free energy in the solar corona may be abruptly released either by a global magnetic topological instability in a catastrophic manner (e.g., Forbes and Isenberg, 1991; Isenberg et al., 1993; Forbes and Priest, 1995; Hu et al., 2003) or by a fast magnetic reconnection across preexisting or rapidly developing electric current sheets (e.g., Antiochos et al., 1999; Forbes and Lin, 2000; Lin and Forbes, 2000). Although the two ways of energy release are possible in the corona, the latter has often been invoked in previous studies with implications in solar active phenomena. However, such a mechanism is conditioned by the preexistence or a rapid formation of electric current sheets. Then a question remains: how can the current sheet exist stably or be formed rapidly in the corona right before reconnection? Moreover, a substantial heating of plasma must occur, but this is not a general feature for CMEs (e.g., MacQueen and Fisher, 1983). Therefore, it is necessary to find a mechanism that causes fast release of magnetic energy without remarkable heating and leads to a rapid formation and development of current sheets as well. The first way of energy release mentioned above is exactly such a mechanism.

Various theoretical models, including catastrophic models of coronal flux ropes as well as other viable scenarios, were proposed and used to simulate solar explosions such as flares, prominence eruptions, and CMEs (see Forbes, 2000; Low, 2001; and references therein). We give an

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overview, not intended to be exhaustive, of the history and development of the catastrophe models in this paragraph. For more details please refer to the reviews written by Lin et al. (2003) and Hu (2005). To our knowledge, the earliest flux rope catastrophe model is attributed to Van Tend and Kuperus (1978) and Van Tend (1979) who approximated the flux rope by a wire current filament and concluded that a loss of equilibrium occurs if the current in the filament exceeds a critical value. However, in their model and subsequent similar ones, the field of the wire filament and the background field are freely reconnected, so the ideal MHD condition is disregarded. Soon their simple wire filament model was refined and replaced by the so-called thin-rope model (e.g. Forbes and Isenberg, 1991; Isenberg et al., 1993; Lin et al., 1998), in which the ideal MHD condition is taken into account and thus electric current sheets appear in the solution. The flux rope is thin in the sense that its radius is far smaller than the length scale of the photospheric field, an approximation purely for analytical tractability. The thin-rope model was then extended to numerical rope models (e.g., Hu et al., 2003), where the rope is finite in radius. Such models were referred to as thick-rope models by Hu (2005).

The studies of MHD catastrophe of coronal flux rope systems have confirmed the possibility that the magnetic energy stored in the corona is released by a global magnetic topological instability, which is essentially an ideal MHD process. The instability takes place in a catastrophic manner, and the plasma is accelerated by the Lorentz force. As a result, the magnetic energy is mainly transformed into the kinetic energy of plasma. In the meantime, current sheets are bound to form as the eruptive flux rope drags magnetic field lines outwards. In order for this mechanism to work, one must find magnetic configurations with a catastrophic behavior, and evaluate the magnetic energy of the system at the catastrophe point, which is also called the energy threshold representing the maximum magnetic energy that can be stored in the system. There is no compelling reason that the threshold energy for a catastrophe should exceed the open-field energy. If the latter is larger, a CME-like expulsion is not expected unless magnetic reconnection sets in to re-close part of the background field that is opened up after a catastrophe (see, e.g., Lin and Forbes, 2000). However, if the threshold energy is larger, then there may be enough energy to open up the background field and accelerate a CME out of the corona, simultaneously. That the second possibility exists is significant as shown in, e.g., Hu et al. (2003) and Li and Hu (2003).

We will summarize some recent results obtained in the study of coronal flux rope catastrophe in the following with emphasis on the catastrophic energy threshold. To further examine how the magnetic energy be released during the catastrophe, a detailed analysis of the force balance for the flux rope in either equilibrium before or eruption after catastrophe is addressed in section 3. To disentangle the contributions made by the ideal MHD catastrophe and resistive magnetic reconnection to CME dynamics, we construct a flux rope catastrophe model in the corona and solar wind and compare different cases in which we either prohibit or allow magnetic reconnection to take place across rapidly-growing current sheets during the eruption. Finally, we conclude this paper with several comments on how the future KuaFu mission (Tu et al., 2007) may contribute to our understanding of the physics of solar eruptive phenomena.

2. Coronal flux rope catastrophe

The so-called flux rope is defined as a twisted loop, a typical structure in the corona. Theoretically, the flux rope must exist for the support of prominences against gravity (Low and Hundhausen, 1995), and it has two types of configurations, inverse and normal, according to the types of associated prominences. To our knowledge, most flux rope models so far belong to the inverse type. It is presently impossible to directly observe the flux rope in the corona. Nevertheless, Yan et al. (2001) claimed that they found a flux-rope like structure in the corona through a reconstruction of the coronal force-free field based on vector magnetogram data observed at the photosphere.

For a magnetic configuration with an isolated flux rope, we may introduce a set of parameters to characterize the properties of the system. For the rope, one may take, say, its annular and axial magnetic fluxes and the total mass in the rope. One may also choose some appropriate parameters to characterize the background field and plasma

surrounding the flux rope of interest. All these parameters are referred to as "physical parameters". On the other hand, several parameters are introduced to describe the geometrical features of the flux rope, for instance, the height of the rope axis and the length of the vertical current sheet, which is formed below the rope when it breaks away from the solar surface and erupts upwards. Now we may select one of the physical parameters as the control parameter that is changeable, and see the variation of the geometrical parameters in response to the change of the selected physical parameter. In studying the parametric dependence of an equilibrium state, we often find that a discontinuity can be encountered so that a small change in the chosen parameter of variation produces an abrupt change in the configuration of the equilibrium state. Then we say that the system has a catastrophic behavior and identify the position of the jump as the catastrophic point.

A catastrophe can be caused by a change of the rope properties, a change of the background field or both. Let us give two typical examples. The first is shown in Fig. 1, a thin-rope model in Cartesian geometry developed by Forbes and Priest (1995), where λ is the half-distance between two point sources on the photosphere, h the height of the rope axis, and R_0 the radius of the flux rope. The magnetic configurations shown in panels (1b) - (1d), which are associated with different values of λ, are plotted in the semi-infinite $x-y$ plane with the surface $y=0$ corresponding to the photosphere. The catastrophe is caused by a decrease of λ to be caused presumably by converging photospheric motions. The location where current sheets start to form is pointed out in the left panel of this figure. It can also be seen from this panel that the catastrophic curve of h versus λ is S-shaped with a finite jump for h from 1 to 9. The second example is a thick-rope model, developed by Sun and Hu (2005). The flux rope is embedded in a quasi-static helmet streamer surrounded by a steady solar wind, and the catastrophe is caused by a slight change of one of the physical parameters of the flux rope. The flux rope stays in equilibrium before and erupts upward after catastrophe. Fig. 2 shows an eruption of the flux rope right after the catastrophic point in terms of the axial flux of the rope. The rope breaks away from the solar surface and erupts to infinity, forming a vertical current sheet below, as mentioned above. The corresponding catastrophic curve, i.e., the height of the rope axis versus the axial flux of the rope, turns out to be fold-shaped in this case.

An important issue is the catastrophic energy threshold, which is defined as the magnetic energy of the flux rope system at the catastrophic point, as mentioned previously. Two decades ago, Aly (1984) put forward a conjecture saying that the magnetic energy that can be stored in a force-free field with given normal component and at least one end of each field line anchored at the solar surface can not exceed the open field energy with the same normal component at the solar surface. The issue raised by this conjecture is important to the catastrophe theory since one would expect that the energy threshold is larger than the corresponding open field energy so that after the background field is opened up by the erupting flux rope, there is still a certain amount of magnetic free energy left to produce a reasonable eruption, as mentioned previously in the text. Nevertheless, the Aly conjecture does not apply to the situations studied by most present flux rope models which have been simplified as two-dimensional (2-D) analyses. In these models, the field lines of the flux rope are levitating in the corona and not anchored to the solar surface. We point out in passing that an infinite amount of energy is required to open up a closed magnetic field in 2-D Cartesian geometry (Hu et al., 2003), therefore, it is energetically impossible to open the overlying field and to let the flux rope escape to infinity without magnetic reconnection, as demonstrated by previous catastrophe models assuming Cartesian geometry (e.g., Lin and Forbes, 2000). On the other hand, in the spherical geometry the open-field energy is finite and it can be exceeded by the flux rope system as already shown by many calculations (e.g., Weber and Sturrock, 2001; Choe and Cheng, 2002; Hu et al., 2003; Li and Hu, 2003; Flyer et al., 2004; Sun and Hu, 2005; Zhang et al., 2005; Peng and Hu, 2005; Ding and Hu, 2006; Chen et al., 2006a). Another basic difference between 2-D Cartesian and spherical models from the point of view of force analysis will be mentioned in Section 3. It was calculated that the energy threshold is larger than the corresponding open field energy by about 8% for coronal flux rope systems either without (Li and Hu, 2003) or with a solar wind (Sun and Hu,

2005) for a closed or partly open dipolar background field. More careful analyses revealed that the energy threshold depends slightly on the physical properties of the rope (Chen et al., 2006a) and the background field (Peng and Hu, 2005; Ding and Hu, 2006). Thus, in 2-D spherical geometry it is possible to have the flux rope erupt to infinity when taking the ideal MHD catastrophe as the only energy release process. This has been confirmed with the numerical thick-rope models. It is also true that the eruptive speed can be significantly enhanced after magnetic reconnection sets in across the rapidly-developing current sheets, as will be illustrated in the following section.

Based on the studies of MHD catastrophe of coronal flux rope systems mentioned above, we argue that MHD catastrophe is probably the main means of energy release for CMEs at least in the initial phase. It releases energy without ohmic heating, especially suitable for CMEs without associated flares. A by-product of the catastrophe is the formation of one or more electric current sheets, which proceeds at the Alfvénic time scale. This provides proper sites for fast magnetic reconnection and answers the question how current sheets are formed rapidly right before the occurrence of magnetic reconnection. Such a reconnection further releases the magnetic energy and should be responsible for a solar flare associated with a CME event.

So far most flux rope models have been limited to 2-D analyses, as mentioned previously. In 3-D cases, the two ends of a flux rope are believed to be anchored to the solar surface. If the Aly Conjecture is correct in this situation, the catastrophic energy threshold must be less than the corresponding open field energy. Magnetic reconnection is then necessary to make a catastrophe develop into an eruption. So the catastrophe plays a role of trigger for CMEs in this case. Nevertheless, Li and Hu (2003) inferred that the Aly Conjecture may become invalid for systems with catastrophic behavior. Such an inference deserves further elaborations.

3. Force balance of the rope in equilibrium or eruption and effects of reconnection on rope dynamics

Now we turn to another important issue, the force balance problem for the flux rope that is in equilibrium or eruption. Chen et al. (2006b) made such an analysis for a flux rope embedded in either a bipolar or a quadrupolar background field. Since the magnetic energy is dominant over other forms of energy near the Sun, we only analyze the interplay between different pieces of magnetic forces, which are exerted by coronal currents inside and outside the rope as well as the potential field with the same normal component on the photosphere as the background field. For the equilibrium situation, the resultant magnetic force acting on the flux rope vanishes. On the other hand, if the rope erupts after catastrophe, it was found that the resultant force is upward, and thus the flux rope undergoes a continuous acceleration by the Lorentz force. Fig. 3 shows the temporal profiles of various magnetic forces acting on the flux rope and the resultant force (Σf) as well during its eruption right after catastrophe. The background field is a partly open bipolar field with an equatorial current sheet extending to infinity, and magnetic reconnection has been prohibited in both this sheet and the newly formed current sheet below the erupting rope. These forces are produced by the initial background potential field (f_p), the azimuthal current in the rope and its image ($f_{R\varphi}$), the poloidal current in the rope (f_{Rp}), the equatorial current sheet above the rope inherent in the background field (f_{c1}), and the newly formed vertical current below the rope (f_{c2}). We emphasize that the self-interaction of the azimuthal current inside the rope by itself results in an outward radial force on the rope. This force comes from the curvature of the rope surrounding the Sun, which is called the toroidal or "hoop" force by Chen (1989) and Krall et al. (2000) and the rope curvature force by Lin et al. (1998). Note that in the 2-D Cartesian models this self-force is trivially zero by the symmetry of an infinitely long straight current, another basic difference between 2-D Cartesian and spherical models as mentioned previously. As clearly seen from Fig. 3a, the primary lifting force is $f_{R\varphi}$ whereas the primary pulling force is f_p. Fig. 3b is a local enlargement of Fig. 3a to illustrate clearly the contributions of f_{Rp}, f_{c1}

and f_{c2} and the variation of the resultant force. After about 20 minutes Σf changes from nearly zero to positive, leading to a remarkable acceleration of the erupting flux rope. Notice that the newly formed current sheet provides an additional pulling force. Consequently, a weakening and suppression of the current sheet by reconnection leads to a further acceleration of the flux rope, as confirmed by the following calculations.

As a first step to disentangle the contributions made by the ideal MHD catastrophe and resistive magnetic reconnection to CME dynamics, Chen et al. (2007) constructed a flux rope catastrophe model in the corona and solar wind and compared different cases in which magnetic reconnection is either prohibited or allowed to take place across the rapidly-developing current sheets. For simplicity, a polytropic process with the polytropic index $\gamma = 1.05$ is assumed to produce the background corona and solar wind solution. One result of this model is presented in Fig. 4 for the case with the magnetic field strength at the polar hole on the solar surface taken to be 16 G. The figure shows the velocity profiles of different parts of the flux rope system, including the cusp point (in dotted), the rope top (in dashed), the rope axis (in solid), and the rope bottom (in dot-dashed), thick curves for the reconnection case and thin for the case without reconnection. It can be seen that the flux rope undergoes an initial slow acceleration, followed by a fast one, and a slight deceleration after it reaches a peak speed. The results are essentially consistent with observed velocity profiles of CMEs (e.g., Zhang and Dere, 2006). Comparing the solutions for the case with and without magnetic reconnection, we can see that CMEs, even fast ones, can be produced taking the ideal MHD catastrophe as the only process of magnetic energy release. Nevertheless, the eruptive speed is significantly enhanced after magnetic reconnection sets in.

4. Suggestions on the diagnosis of energy release processes of CMEs with KuaFu

Now let us come to the final topic: What can observers do with the future KuaFu mission to clarify the roles of MHD catastrophe and magnetic reconnection in energy release processes involved in CMEs?

The KuaFu mission is designed to observe the complete chain of space weather events from the solar atmosphere to geospace with three satellites, including KuaFu-A at the L1 libration point observing solar Hard X-ray, EUV and white-light emissions, radio waves, local plasma and magnetic field, and energetic particles, and KuaFu-B1 and B2 in elliptical polar orbits elaborated to continuously observe the northern polar auroral oval (Tu et al., 2007). Although KuaFu is still at its early stage of development, various payload plans have been proposed. Among them, we are particularly interested in the following ones mounted at KuaFu-A: an EUV Disk Imager (EDI), a Multi Order Solar EUV Spectrograph (MOSES for KuaFu), a Hard X-Ray and Gamma-ray Spectrometer (HXGR), a Lyman-α coronagraph, and a white light coronagraph. In the following we briefly discuss some relevant characteristics of these instruments and show how they may contribute to our understanding of solar eruptions.

The EDI instrument will provide a continuous imaging in the Lyman-α wavelength of 121.6 nm with high spatial and temporal resolution. The polarization of this line will also be recorded simultaneously. Complementary with ground-based or space-borne magnetograms, these images with the deduced polarization enable us to reveal the dynamical features and get information about the associated magnetic topology in both large and small scales before and after eruptions. With the Lyman-α imaging channel of EDI (observing from the disk up to 1.1 $R_{\odot}$), the Lyman-α (from 1.1 to 2.5 $R_{\odot}$) and white-light coronagraphs (from 2.5 to 15 $R_{\odot}$), KuaFu can provide a continuous tracking of a CME event from the disk source to 15 $R_{\odot}$. The temporal profiles of the various parts of the eruptive structure can be determined so as to put constraints on the acceleration mechanism of individual CME events. These observations are pressingly wanted by the solar physics community especially after the failure of LASCO-C1 in the June of 1998. The MOSES for KuaFu is a slitless imaging spectrograph at 3 spectral orders in the He II 30.4 nm line providing high-resolution images and simultaneous measure of the line of sight velocity on the solar disk with an accuracy of 20 km s^{-1}. MOSES can be used to find out the exact source region of the CME by e.g., detecting outflowing materials in coronal dimming regions, and mea-

sure the flux rope twist and CME velocity in the early phases of eruption. It should be kept in mind that although this set of instruments is designed to cover many aspects of a solar phenomena, the data set they offer should be combined with complementary data from instruments of other space crafts and ground based observatories. For example, the K-Coronameter of the High Altitude Observatory in Hawaii observes CMEs with a field of view from the limb to 2 $R_\odot$ in heliocentric distance, will play a complementary role to the proposed KuaFu coronagraphs.

These new coordinated measurements by KuaFu are certainly important to our understanding of the energy storage and release processes, trigger, initiation and further acceleration of CMEs, and will greatly facilitate our endeavor in evaluating the roles of reconnection and catastrophe in CME energetics and dynamics. A specific relevant observational task will be to evaluate the variation rate of magnetic flux as the coronal dimming region forms and disappears in a CME event, and to see how they are related to the CME kinematics. The latter rate is supposed to represent the total magnetic reconnection rate associated with the formation of the post-flare loops and giant X-ray arches observed in the lower corona (Forbes and Lin, 2000). The work along this line has been carried out by several authors with SOHO measurements, e.g., Jing et al. (2005) and Qiu and Yurchyshyn (2005). With the MOSES for KuaFu to detect the coronal dimming or the source region connected to the CME, the EDI to measure the polarization of the Lyman-α line which contains information on the coronal magnetic field vector, and the HXGR to assess the timing of reconnection, it is hopeful to obtain a more accurate description of the reconnection rate, which can be further employed to constrain theoretical endeavors in evaluating the roles of reconnection and catastrophe in CME energetics and dynamics.

This work was supported by the National Basic Research Program of China (2006 CB806304) and the National Natural Science Foundation of China (40404013, 40574064, and 10233050).

REFERENCES

Aly, J. J. On some properties of force-free magnetic fields in infinite regions of space, Astrophys. J. 283, 349-362, 1984.

Antiochos, S. K., DeVore, C. R., Klimchuk, J. A. A model of solar mass ejections, Astrophys. J. 510, 485-493, 1999.

Chen, J. Effects of toroidal forces in current loops embedded in a background plasma, Astrophys. J. 338, 453-470, 1989.

Chen, Y., Chen, X. H., Hu, Y. Q. Catastrophe of coronal flux rope in unsheared and sheared bipolar magnetic fields, Astrophys. J. 644, 587-591, 2006a.

Chen, Y., Hu, Y. Q., Sun, S. J. Catastrophic eruption of magnetic flux rope in the corona and solar wind with and without magnetic reconnection, Astrophys. J. 2007, submitted.

Chen, Y., Li, G. Q., Hu, Y. Q. Force balance analysis of a coronal magnetic flux rope in equilibtium or eruption, Astrophys. J. 649, 1093-1099, 2006b.

Choe, G. S., Cheng C. Z. Energy of force-free magnetic fields in relation to coronal mass ejections, Astrophys. J., 574, L179-L182, 2002.

Ding, J. Y., Hu, Y. Q. Coronal flux rope catastrophe in octapole magnetic fields. Solar Phys. 233, 45-55, 2006.

Flyer, N., Fornberg, B., Thomas, S., Low, B. C. Magnetic-field confinement in the solar corona. I. Force-free magnetic fields. Astrophys. J. 606, 1210-1222, 2004.

Forbes, T. G. A review on the genesis of coronal mass ejections, J. Geophys. Res. 105, 23153-23165, 2000.

Forbes, T. G., Isenberg, P. A. A catastrophe mechanism for coronal mass ejections, Astrophys. J. 373, 294-307, 1991.

Forbes, T. G., Lin, J. What can we learn about reconnection from coronal mass ejections? J. Atmos. Sol.-Terr. Phys. 62, 1499-1507, 2000.

Forbes, T. G., Priest, E. R. Photospheric magnetic field evolution and eruptive flares, Astrophys. J. 446, 377-389, 1995.

Hu, Y. Q. The catastrophe of coronal magnetic flux ropes in CMEs. in K. P. Dere, J. Wang, and Y. Yan (eds), Coronal and Stellar Mass Ejections, Proceedings IAU Symposi7um No.226, 263-273, 2005.

Hu, Y. Q., Li, G. Q., Xing, X. Y. Equilibrium and catastrophe of coronal flux ropes in axisymmetrical magnetic field, J. Geophys. Res. 108, 1072, doi:10.1029/2002JA009419, 2003.

Isenberg, P. A., Forbes, T. G., Demoulin, P. Catastrophic evolution of a force-free flux rope: a model for eruptive flares, Astrophys. J. 417, 368-386, 1993.

Jing, J., Qiu, J., Lin, J., Qu, M., Xu, Y., Wang, H. Magnetic reconnection rate and flux-rope acceleration of two-ribbon flares, Astrophys. J. 620, 1085-1091, 2005.

Krall, J., Chen, J., Santoro, R. Drive mechanisms of erupting solar magnetic flux ropes, Astrophys. J. 539, 964-982, 2000.

Li, G. Q., Hu, Y. Q. Magnetic energy of force-free fields with detached field lines. Chin. J. Astron. Astrophys. 3, 555-562, 2003.

Lin, J., Forbes, T. G. Effects of reconnection on the coronal mass ejection process, J. Geophys. Res. 105, 2375-2392, 2000.

Lin, J. Forbes, T. G., Isenberg, P. A., Demoulin, P. The effect of curvature on flux-rope models of coronal mass ejections, Astrophys. J. 504, 1006-1019, 1998.

Lin, J., Soon, W., Baliunas, S. L. Theories of solar eruptions: a review, New Astronomy Rev., 47, 53-84, 2003.

Low, B. C. Coronal mass ejections, magnetic flux ropes, and solar magnetism. J. Geophys. Res. 106, 25141-25163, 2001.

Low, B. C., Hundhausen, J. R. Magnetostatic structures of the solar corona, II, The magnetic topology of quiescent prominences, Astrophys. J., 443, 818-836, 1995.

MacQueen, R. M., Fisher, R. R. The kinematics of solar inner coronal transients, Sol. Phys. 89, 89-102, 1983.

Peng, Z., Hu, Y. Q. Catastrophe of coronal magnetic rope in partly open multipolar magnetic field, Chin. Astron. Astrophys. 29, 396-403, 2005.

Qiu, J., Yurchyshyn, V. B. Magnetic reconnection flux and coronal mass ejection velocity, Astrophys. J. 634, L121-L124, 2005.

Sun, S. J., Hu, Y. Q. Coronal flux rope catastrophe in the presence of solar wind, J. Geophys. Res. 110, A05102, doi:10.1029/2004JA010905, 2005.

Tu, C. Y., Schwenn, R., Donovan, E. et al., Space Weather Explorer - The KuaFu Mission, Advances in Space Research, 2007, submitted.

Van Tend, W. The onset of coronal transients, Sol. Phys., 61, 89-93, 1979.

Van Tend, W., Kuperus, M. The development of coronal electric current systems in active regions and their relation to filaments and flares, Sol. Phys., 59, 115-127, 1978.

Weber, M. A., Sturrock P. A. Energy content of a possible pre-CME magnetic field configuration, Trans. Amer. Geophys. Union: Spring Meeting Abstracts, SH51B-05, 2001.

Yan, Y. H., Deng, Y. Y., Karlicky, M., et al. The Magnetic rope structure and associated energetic processes in the 2000 July 14 solar flare, Astrophys. J. 551, L115-L119, 2001

Zhang, J., Dere K. P., A statistical study of main and residual accelerations of coronal mass ejections, Astrophys. J. 649, 1100-1109, 2006.

Zhang, Y. Z., Hu, Y. Q., Wang, J. X. Double catastrophe of coronal flux rope in quadrupolar magnetic field. Astrophys. J. 626, 1096-1101, 2005.

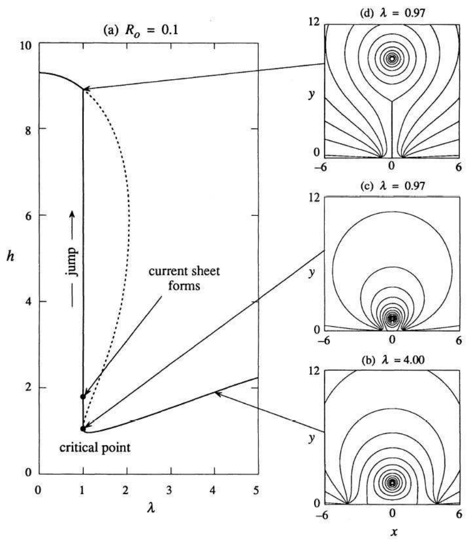

Fig. 1.— (a) Flux rope height, h, as a function of the separation half-distance, λ, between the photospheric sources. R_0 represents the radius of the flux rope. Panels (b), (c) and (d) show magnetic configurations at the 3 locations indicated in (a) [after Forbes and Priest, 1995].

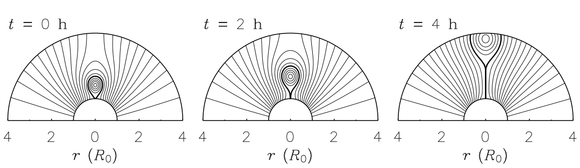

Fig. 2.— Magnetic configurations at three separate times, showing an eruption of the flux rope right after the catastrophic point [after Sun and Hu, 2005].

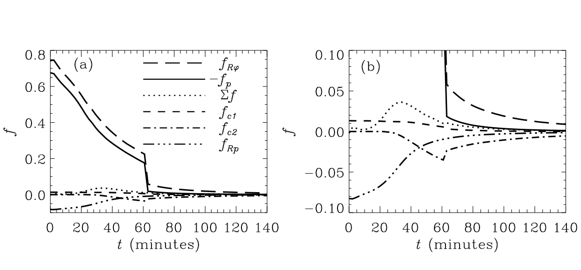

Fig. 3.— Temporal profiles of magnetic forces on the eruptive flux rope per radian for the bipolar background field case [after Chen et al., 2006b].

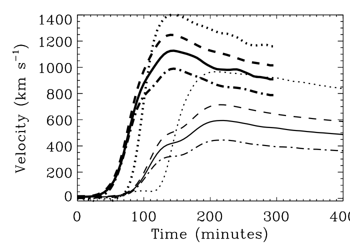

Fig. 4.— Temporal profiles of velocity for the cusp, the rope top, the rope axis, and the rope bottom in succession from higher to lower, thick curves for the reconnection case and thin for the case without reconnection.